Fermi National Accelerator Laboratory

FERMILAB-Conf-98/292-E
CDF and D0

MSSM and Higgs Searches at the Tevatron

Juan A. Valls
For the CDF and D0 Collaborations

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Rutgers, the State University of New Jersey
P.O. Box 849, Piscataway, New Jersey 08904

September 1998

Published Proceedings of the *XXIX International Conference on High Energy Physics*,
TRIUMF, Vancouver, Canada, July 23-29, 1998

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

Disclaimer

Distribution

MSSM AND HIGGS SEARCH AT THE TEVATRON

Juan A. Valls

Rutgers, The State University of New Jersey, P.O. Box 849, Piscataway, NJ 08904, USA
E-mail: valls@fnal.gov

In this paper a summary of present CDF and DØ results on supersymmetry and Higgs searches at Tevatron is presented. Analysis include results from a variety of signatures: missing E_T and jets (or leptons and jets) for squark/gluino searches, trileptons and missing E_T for gaugino searches and, for the first time, charmed-tagged jets and missing E_T as a new signature for stop quark pair production. We show also results for various searches of standard and non-standard model Higgs bosons in hadron collisions. The seeked signature is Higgs associated production with a vector boson. Different channels involve jets and leptons from vector boson decays and b-tagged jets or photons from Higgs decays.

1 Introduction

The Fermilab Tevatron $p\bar{p}$ collider has provided collisions at $\sqrt{s} = 1.8$ TeV during two recent running periods. In Run IA (1992-93) a total accumulated 20 pb^{-1} of data was collected by CDF and 15 pb^{-1} by DØ , and in Run IB (1995-96) 109 pb^{-1} and 90 pb^{-1} were collected by CDF and DØ respectively. The results presented here correspond to partial and complete analysis of this large sample of data.

Hints for supersymmetric (SUSY) particles like squarks, gluinos, and gauginos have been searched in classical channels at hadron colliders, including missing E_T ($\not\!\!E_T$) + jets or $\not\!\!E_T$ + jets + leptons. Other SUSY searches with signatures involving photons in the final state are reported in a different review [1] within these proceedings. For the first time, CDF reports a search for direct stop pair production using c-tagged jets + $\not\!\!E_T$, improving the sensitivity reached in previous analysis.

Although with limited sensitivity, Higgs boson searches including new channels and signatures have been performed and combined. Search techniques have been developed and proved to be promising for the next Tevatron run, when an approximate twenty-fold increase in the total integrated luminosity is expected.

Results are interpreted in general unification scenarios along the line of supergravity (SUGRA), which mediates the interaction needed for supersymmetry breaking. This results in a great simplification on the number of parameters at the unified energy scale, which are defined to be M_0 for the common scalar (squark and slepton) masses, and $M_{1/2}$ for the common gaugino masses. Three other parameters define the Higgs sector of the model: $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets, A_0, the universal trilinear coupling constant, and the sign of μ, the mixing parameter in the Higgsino mass matrix.

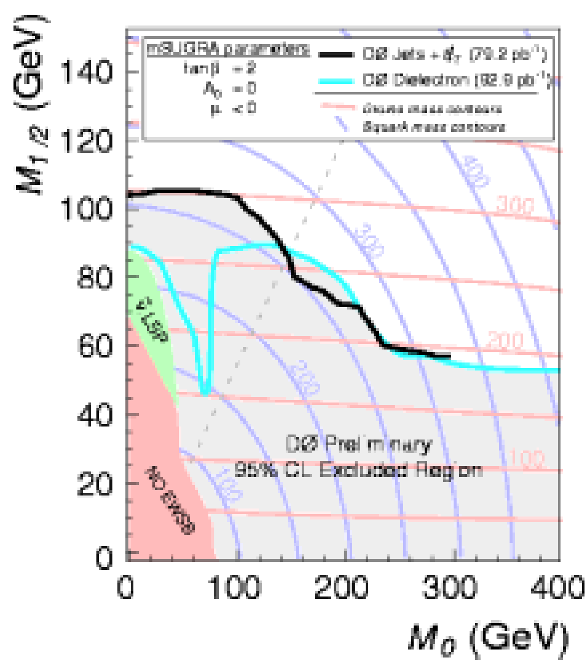

Figure 1: DØ 95% CL excluded region in the $M_0 - M_{1/2}$ plane.

2 SUSY Searches

2.1 Squark and Gluino Searches

Both CDF and DØ have performed searches for squarks and gluinos in events with jets + $\not\!\!E_T$. The signature arises from the ultimate decays of these sparticles into jets and lightest neutralinos. The analysis reported here corresponds to an update of the previous DØ [2] results with 79.2 pb^{-1} of Run IB data. CDF results [3] for 19 pb^{-1} of Run IA data will also be briefly summarized.

The DØ search requires one jet with $E_T > 115$ GeV and two more jets with $E_T > 25$ GeV. A $\not\!\!E_T > 75$ GeV as well as a total scalar sum of jet E_T's (excluding the leading jet) > 100 GeV are required. Further cuts require the $\not\!\!E_T$ to be uncorrelated in ϕ with any jet. After these cuts, remaining standard model (SM) backgrounds are $t\bar{t}$, W/Z and QCD production. The DØ analysis is interpreted in the context of a minimal SUGRA model with fixed $\tan\beta$, A_0, and sign of μ. The results are shown in Figure 1 as a function of M_0 and $M_{1/2}$. All models with $M_{\tilde{q}} < 250$ GeV/c^2 are excluded. For models with $M_{\tilde{q}} = M_{\tilde{g}}$, a common mass below 260 GeV/c^2 is excluded.

The limits derived from the Run IA CDF analysis are shown in Figure 2 as the hashed region area in the $M_{\tilde{q}} - M_{\tilde{g}}$ plane. In this case a modified SUGRA-inspired framework is used to interpret the results. The model

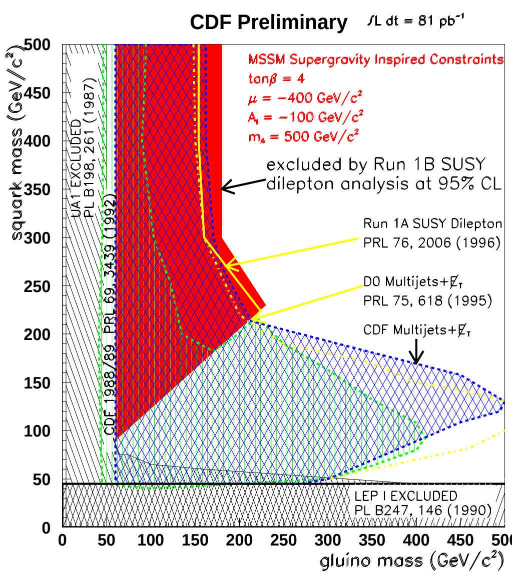

Figure 2: CDF 95% CL excluded region in the $M_{\tilde{q}} - M_{\tilde{g}}$ plane from the lepton + $\not{E}_T$ and the LS dilepton analysis.

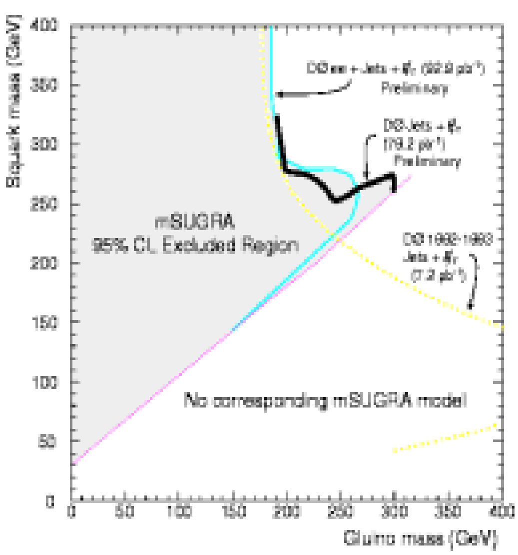

Figure 3: DØ 95% CL excluded region in the $M_{\tilde{q}} - M_{\tilde{g}}$ plane.

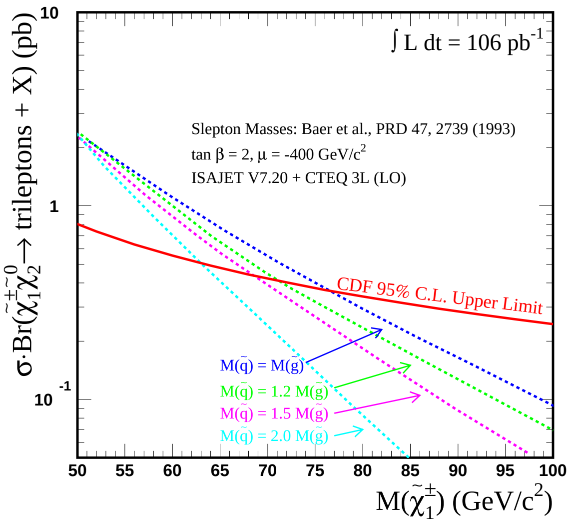

Figure 4: CDF 95% CL limits on $\sigma_{\tilde{\chi}_1^\pm \tilde{\chi}_2^0} BR(\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow 3l + X)$ versus $\tilde{\chi}_1^\pm$ mass for representative points in the MSSM parameter space.

is specified by using as input parameters $M_{\tilde{q}}$, $M_{\tilde{g}}$, M_A, $\tan\beta$, and the magnitud and sign of μ. At the 95% CL CDF excludes common squark and gluino masses $M_{\tilde{q}} = M_{\tilde{g}} < 216$ GeV/c^2, and $M_{\tilde{g}} < 173$ GeV/c^2, independent of squark mases. DØ has also produced an experimental limit in the $M_{\tilde{q}} - M_{\tilde{g}}$ plane using the 79.2 pb^{-1} of Run IB data. Their results are shown in Figure 3. The results of these analysis do not change substantially as parameters are varied within the theoretical framework.

The limits from the jets + $\not{E}_T$ analysis can be extended by searching for signatures with isolated lepton pairs. These arise from cascade decays of gluinos to quark pairs via charginos/neutralinos which decay to leptons. These channels produce relatively clean experimental signals, in particular if the lepton pairs are required to be like-sign (LS). Latest CDF LS dilepton (e, μ) results [4] and DØ ee results [5] from these channels in the $M_{\tilde{q}} - M_{\tilde{g}}$ plane are shown in Figures 2 and 3 respectively.

2.2 *Associated Gaugino Pair Production*

Both CDF [6] and DØ [7] have searched for associated chargino-neutralino pair production $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ using the complete Run I data sample. Assuming SUGRA constrains the chargino can decay to $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 l \nu$ and the neutralino to $\tilde{\chi}_2^0 \rightarrow l^+ l^-$, giving rise to very distinct signatures with three leptons + $\not{E}_T$ and small SM backgrounds. Only the CDF analysis will be reported here. The search include four channels: $e^+e^-e^\pm$, $e^+e^-\mu^\pm$, $\mu^+\mu^-e^\pm$, and $\mu^+\mu^-\mu^\pm$. No candidates are found while 0.3 events are expected

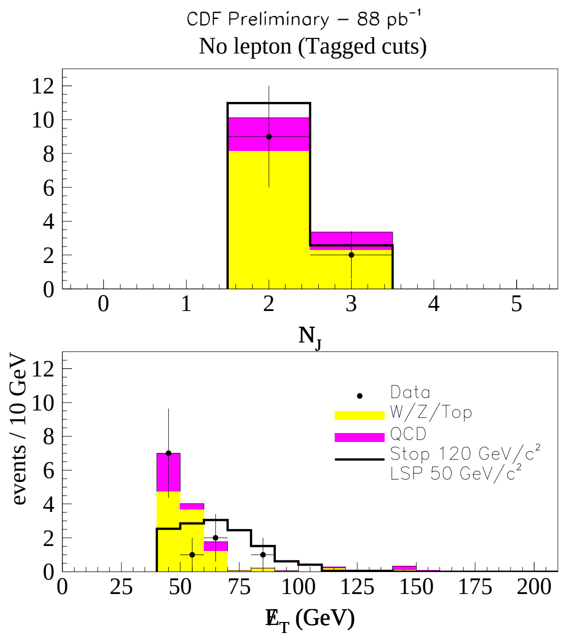

Figure 5: Jet multiplicity (top) and $\not\!\!E_T$ (bottom) distributions for the pretagged $\tilde{t}\bar{\tilde{t}}$ sample for data, SM backgrounds and signal.

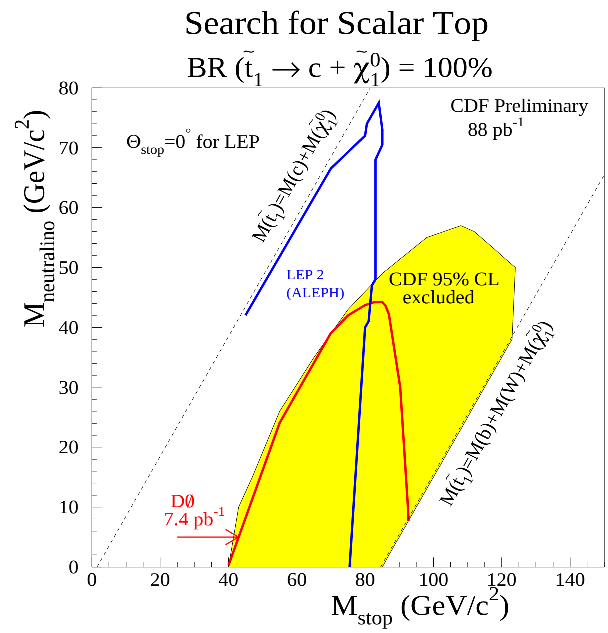

Figure 6: CDF 95% CL excluded region in the $M_{\tilde{t}} - M_{\tilde{\chi}^0_1}$ plane.

from background processes like Drell-Yan (plus a fake lepton), $b\bar{b}$, $c\bar{c}$ and diboson events.

Results are shown in Figure 4 as 95% CL upper limits on the sum of the branching ratio times cross setion for the four channels: $\sigma_{\tilde{\chi}^\pm_1\tilde{\chi}^0_2} BR(\tilde{\chi}^\pm_1\tilde{\chi}^0_2 \rightarrow 3l + X)$. This represents a lower limit of $M_{\tilde{\chi}^\pm_1} > 81.5$ GeV/c^2 and $M_{\tilde{\chi}^0_2} > 82.2$ GeV/c^2 for $\tan\beta = 2$, $\mu = -600$ GeV/c^2 and $M_{\tilde{q}} = M_{\tilde{g}}$.

2.3 Direct Stop Quark Pair Production

As a consequence of the large top mass, the MSSM predicts a large splitting between the two top quark suppersymetry partners, with the lightest one significantly lighter than the top. This stop could be then observable at Tevatron.

CDF has recently finished a preliminar analysis for direct $\tilde{t}\bar{\tilde{t}}$ production using the decays $\tilde{t} \rightarrow c\tilde{\chi}^0_1$ with 88.6 pb^{-1} of data from Run IB. The signature is two acolinear jets from charmed quarks, significant $\not\!\!E_T$, and the absence of leptons in the final state. The analysis requires 2 or 3 jets with $E_T > 15$ GeV and a $\not\!\!E_T > 40$ GeV. The $\not\!\!E_T$ is required to be uncorrelated in ϕ with any jet. After these cuts the main background sources arise from SM W/Z + jets, QCD and $t\bar{t}$ events. Figure 5 shows the jet multiplicity and $\not\!\!E_T$ distributions for data and the different background contributions after the selection cuts. To further reduce backgrounds, a c-tagged jet probability algorithm is, for the first time, utilized in CDF with acceptable efficiencies. After this cut 11 events are left to be compared to a background estimate of 13.5 ± 4.

The 95% CL exclusion region in the $M_{\tilde{t}} - M_{\tilde{\chi}^0_1}$ parameter space is shown in Figure 6. A lower limit of $M_{\tilde{t}} > 120$ GeV/c^2 for $M_{\tilde{\chi}^0_1} = 38$ GeV/c^2 is obtained. The analysis significantly extends the limit as compared to previous analysis from LEP and DØ[8].

Further sensitivity to stop quark pair production is achieved by studying the decays $\tilde{t} \rightarrow \tilde{\chi}^\pm_1 b$, $l\nu b\tilde{\chi}^0_1$ and $\tilde{\chi}^\pm_1 \rightarrow \tilde{\chi}^0_1 l\nu$ with signatures including b jets, leptons and $\not\!\!E_T$. This analysis is in progress within the CDF collaboration. Finally stop quarks could also be detectable through top decays $t \rightarrow \tilde{t}\tilde{\chi}^0_1$ and subsequent $\tilde{t} \rightarrow b\tilde{\chi}^\pm_1$, $bl\nu\tilde{\chi}^0_1$. Results from this channel have already been presented by the CDF collaboration[9].

3 Higgs Searches

3.1 Standard Model Higgs

The standard model provides the simplest mechanism for spontaneous symmetry breaking through the introduction of a scalar field doublet. This leaves a single observable scalar particle, the Higgs boson, with unknown mass but fixed couplings to other particles.

At Tevatron, one of the Higgs production mechanism more likely to be observed is associated production $V + H$ with $V = W, Z$. Both CDF and DØ have searched for this channel using different signatures. Both experiments

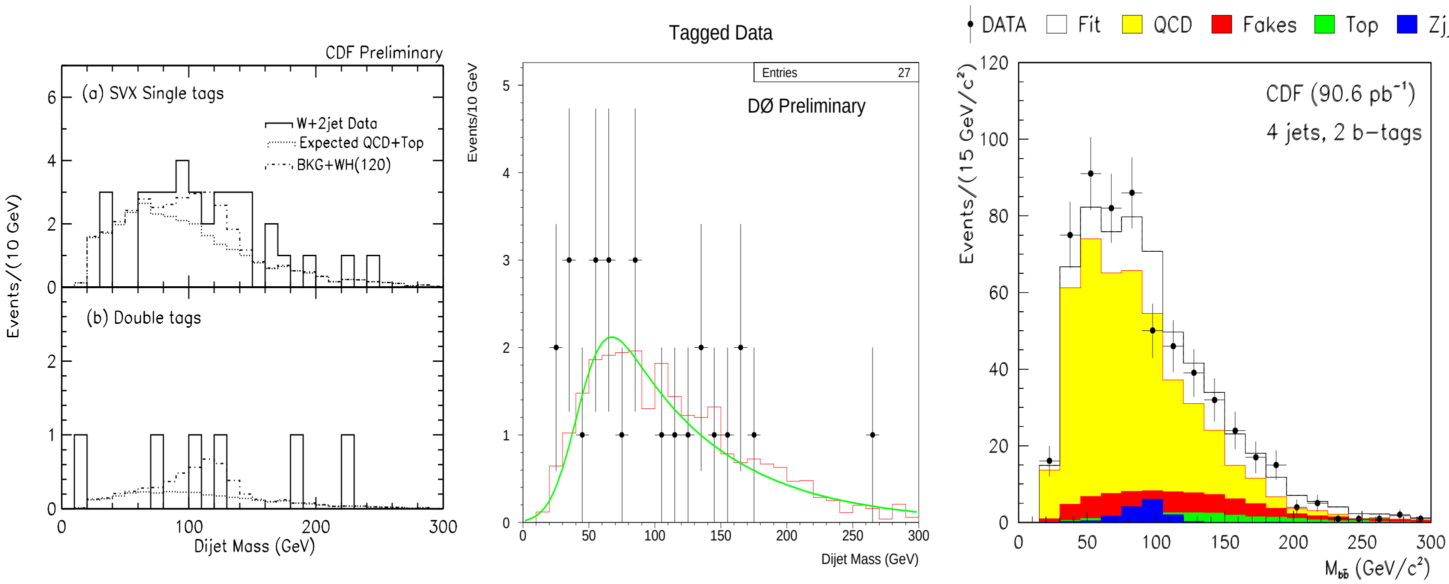

Figure 7: $b\bar{b}$ invariant mass distributions for the CDF and DØ SM Higgs selections: $WH \rightarrow l\nu b\bar{b}$ (left, middle plots) and $VH \rightarrow jjb\bar{b}$ ($V = W, Z$, right plot) compared to the expected backgrounds.

look for an isolated high p_T lepton + $\not\!\!E_T$ to identify the W decay, and jets with b-tags to identify the $b\bar{b}$ Higgs decay [10]. CDF also searches in high jet multiplicity events from hadronic decays of W and Z bosons with the requirement of at least two b-tagged jets [11]. No deviation from the expected SM background contributions is observed in the reconstructed $b\bar{b}$ invariant mass distributions. A likelihood fit is then made to the shape of the observed distributions using a combination of signal and different SM background sources. Figure 7 shows the $b\bar{b}$ invariant mass distribution for the CDF and DØ l + jets WH selection, as well as for the CDF all-hadronic VH selection. In all cases, the data is compared to the expected SM background sources.

DØ has also searched for invisible $\nu\bar{\nu}$ decays of Z bosons in association with a Higgs boson. Muon-tagged jets are utilized to identify b-quark decays of the Higgs, and a $\not\!\!E_T > 35$ GeV cut is further required to reject most of the SM backgrounds.

Figure 8 shows the 95% CL upper limit results on $\sigma(WH)BR(H \rightarrow b\bar{b})$ and $\sigma(ZH)BR(H \rightarrow b\bar{b})$ for the individual CDF and DØ results. Figure 9 shows the 95% CL upper limit results on $\sigma(VH)\beta(H \rightarrow b\bar{b})$ with $V = W, Z$ for the CDF all-hadronic analysis. The same figure shows the combined limit obtained from the all-hadronic and lepton + jets results. The sensitivity of these searches is limited by statistics to a cross section approximately two orders of magnitude larger than the predicted cross section for standard model Higgs production. For the next Tevatron run we hope for an approximately twenty-fold increase in the total integrated luminosity and a substantial increase in the total acceptances

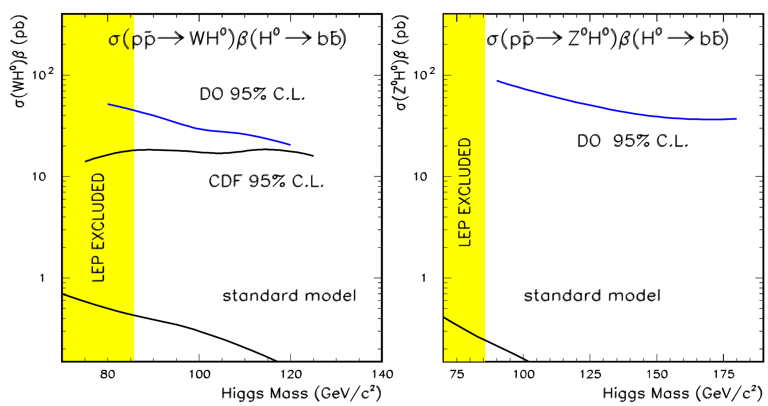

Figure 8: CDF and DØ 95% CL upper limits on $\sigma(WH)BR(H \rightarrow b\bar{b})$ (left) and $\sigma(ZH)\beta(H \rightarrow b\bar{b})$ (right).

by improving the single and double b-tagging efficiencies, and the use of a more efficient, dedicated Higgs trigger.

3.2 MSSM Higgs

A more complex symmetry breaking mechanism occurs in the MSSM, when five observable scalar states are predicted: two charged Higgs particles ($H^{\pm}$), two CP-even scalars (h^0, H^0) and one CP-odd pseudoscalar (A^0). In order to describe the MSSM Higgs sector one has to introduce two additional parameters to describe the properties of the scalar particles and their interactions with gauge bosons and fermions: $\tan\beta$ and the mixing angle α in the neutral CP-even sector.

CDF has presented results on direct and indirect

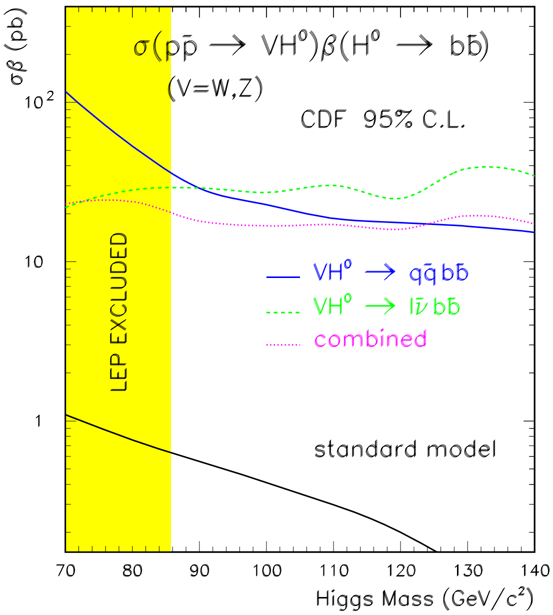

Figure 9: CDF 95% CL upper limits on $\sigma(VH)BR(H \to b\bar{b})$ with $V = W, Z$ from the individual and combined $VH \to l\bar{\nu}b\bar{b}$, $q\bar{q}b\bar{b}$ channels.

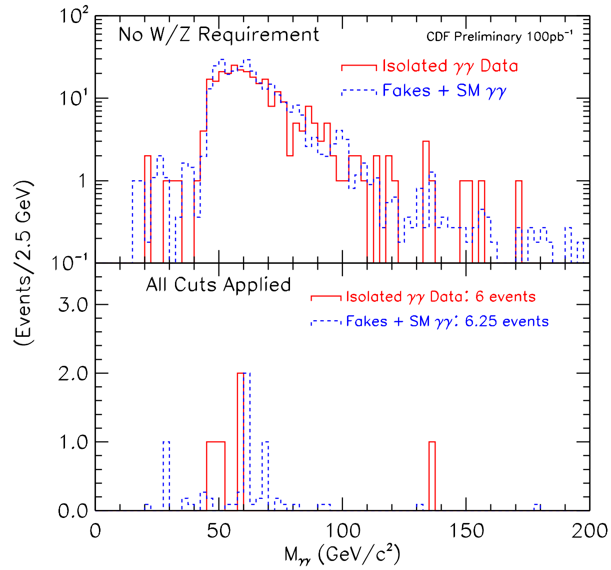

Figure 10: CDF diphoton invariant mass distribution with photon selection cuts only before (top) and after (bottom) the W/Z selection cuts.

Higgs production via top quark decays $t \to H^+ b$ with $H^+ \to \tau\nu$ showing sensitivity to the high and low $\tan\beta$ regions in the $M_{H^\pm}$-$\tan\beta$ plane [12].

More recently, CDF has started an analysis seeking for neutral MSSM Higgs particles produced via the associated production $b\bar{b}\Phi$ with $\Phi = h^0, H^0, A^0$ and $\Phi \to b\bar{b}$. The signature is high multiplicity jets with at least two of them tagged as b-quark jets. In the MSSM, the Yukawa couplings between the Higgs scalars and the b quarks are enhanced for large $\tan\beta$ values with respect to the standard model. With basic parameter choices for the SUSY scale and the stop mixing, CDF derived 95% CL lower mass limits for the neutral Higgs sector of the MSSM as a function of $\tan\beta$. These are preliminary results still not presented by the time of this conference.

3.3 Higgs Decaying to Two Photons

Finally, several extended Higgs models allow a light neutral scalar Higgs, with standard model strength couplings to vector bosons but suppresed couplings to fermions. Such a "bosophilic" Higgs decays dominantly to $\gamma\gamma$ for masses below 90 GeV/c^2 and is most easily detected in the associated production mode with a vector boson.

Both CDF and D$\emptyset$ have analyzed the complete Run I data sample seeking for diphoton signatures + leptons, $\not\!\!E_T$, or jets. The CDF diphoton sample consists of events with two isolated central ($|\eta| < 1.0$) photon candidates with $E_T > 25$ GeV. D$\emptyset$ uses a similar sample with slightly different thresholds. These high p_T photon samples suffer from significant backgrounds from jets misidentified as photons, calculated from independent fake control samples with modified isolation requirements. CDF requires further the presence of a high p_T lepton (e, μ), or $\not\!\!E_T$, or two jets, covering all possible decay channels of the vector bosons. 6 evenys are left with a predicted background of 6.2 ± 2.1. D$\emptyset$ only requires the presence of two additional jets. They find 4 candidates with an expected background of 6.0 ± 2.1 events. Figures 10 and 11 show the diphoton invariant mass distributions before and after the vector boson selection cuts, compared to SM background expectations for CDF and D$\emptyset$ respectively.

CDF results for the 95% CL upper limits on $BR(H \to \gamma\gamma)$ assuming SM production cross section for $W/Z + H$ are shown in Figure 12. The D$\emptyset$ results are presented in Figure 13 as 95% CL upper limits on the production cross section times branching ratio compared to the full "bosophilic" cross section.

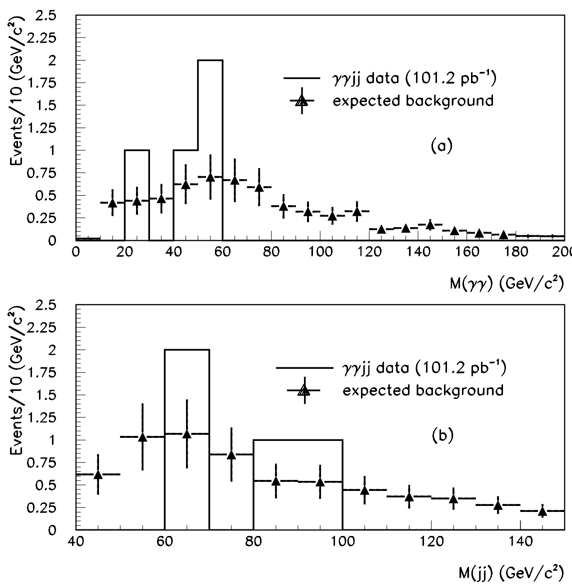

Figure 11: DØ (a) diphoton invariant mass and (b) jet mass distributions compared with expected backgrounds.

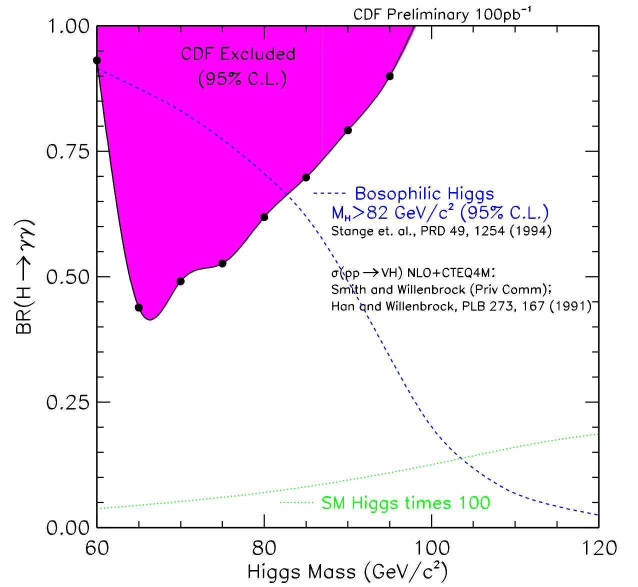

Figure 12: CDF 95% CL upper limit on $BR(H \rightarrow \gamma\gamma)$ as a function of the Higgs mass compared with "bosophilic" and SM branching ratio predictions.

Conclusions

A summary of the present undergoing analysis results from the CDF and DØ collaborations at the Tevatron has been presented. A broad range of signatures corresponding to very different channels have been investigated for hints of new physics in the framework of supersymmetry and several Higgs models including the SM, the MSSM Higgs sector, and "bosophilic" Higgs scenarios. No evidence for any of the channels covered has been found with the present statistics and 95% CL limits on different model parameters have been stablished. The analysis of the Run I data is still not completed and several new results will be reported in the near future.

The Tevatron is scheduled to operate again in Run II by the fall of 1999 with substantial luminosity improvements and an energy reach increased to $\sqrt{s} = 2$ TeV. A twenty-fold increase in statistics is expected by the first years of operation. The Tevatron will be able to significantly probe a large fraction of the expected SUSY mass range. With sufficient integrated luminosity provided by further Tevatron runs, a light intermediate-mass Higgs in the range $80 < M_H < 130$ GeV/c^2 or event above this threshold, will also be accesible.

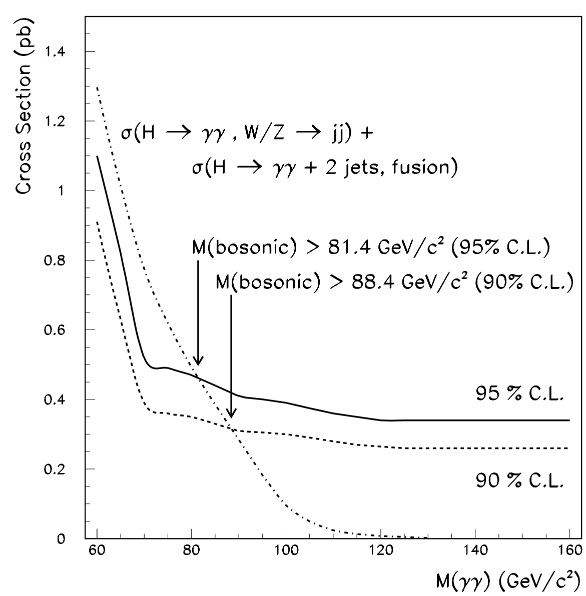

Figure 13: DØ 90% and 95% CL upper limits on the total production cross section times branching ratio for associated production of vector bosons and Higgs decaying to $\gamma\gamma$.

Acknowledgements

I am very grateful to all members of the CDF and DØ exotics physics group at Fermilab for providing me the different material shown in this paper.

References

1. M. Paterno, *Gauge Mediated SUSY Searches at the Tevatron*, these proceedings.
2. B. Abbott *et al.*, Fermilab-Conf-97/357-E.
3. F. Abe *et al.*, Phys. Rev. **D56**, 1357 (1997).
4. F. Abe *et al.*, Phys. Rev. Lett. **76**, 2006 (1996). J.Done, Fermilab-Conf-96-371-E, *Proc. of 1996 DPF, Minneapolis, 1996.*
5. S. Abachi *et al.*, Fermilab-Conf-96-427-E, *Proc. of XXVIII ICHEP, Warsaw, Poland, 1996.*
6. F. Abe *et al.*, Phys. Rev. Lett. **76**, 4307 (1996).
7. B. Abbott *et al.*, Fermilab-Pub-97/201-E.
8. S. Abachi *et al.*, Phys. Rev. Lett. **76**, 2222 (1996).
9. P.J. Wilson, Fermilab-Conf-97-241-E, *Proc. of Les Rencontres de Physique de la Vallee d'Aosta, La Thuile, 1997.*
10. F. Abe *et al.*, Phys. Rev. Lett. **79**, 3819 (1997). S. Abachi *et al.*, *Proc. of XXVIII ICHEP, Warsaw, Poland, 1996.*
11. F. Abe *et al.*, Fermilab-Pub-98-252, Aug. 1998. Submitted to Phys. Rev. Lett.
12. F. Abe *et al.*, Phys. Rev. Lett. **79**, 357 (1997). Fermilab-Conf-97-213-E, *Proc. of the XII Hadron Coolider Physics, SUNY, Stony Brook, 1997.*